Assessment of Transportation Impacts: Use of RADTRAN to Assess Risks of Severe Accidents

by

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This study evaluates the probability of severe transportation accidents and develops inputs to the computer model employed in transportation risk assessments, RADTRAN . We examine in detail the accident rates employed in RADTRAN and the breakdown of these accident rates into accident severity categories. Clearly, the range of possible transportation accidents is large, from fender-denters not likely to release radioactivity to extreme accidents that could shatter fuel cladding and fuel and lead to a major release of radioactivity through damaged seals.

The range of accidents may be characterized with different parameters such as fire temperature and impact speed or strain and cask lead temperature. Different authors have broken down the range of possible accidents into 6, 8 or 20 accident severity categories, depending on the parametric characterization of severe accidents. These accident severities can be further broken down into the population zones of occurrence: rural, suburban and urban.

In this report we review the history of accident probability/consequence estimates determined for previous versions of RADTRAN, up to and including RADTRAN 4.1. This history begins in 1977 with the Nuclear Regulatory Commission's environmental report on transportation, leading up to the most recent analysis in 1991 by Lawrence Livermore Labs. We have carefully

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analyzed all supporting references for the accident severity fractions used in RADTRAN 4.1. We also have analyzed the assumptions employed to derive the accident severity fractions and have been able to reproduce the inputs into RADTRAN II and RADTRAN 4.1. These assumptions are discussed in this report.

We have then compared the accident severity fractions with a range of 38 severe accidents which have actually occurred on the highways and rails to determine whether the accident severity fractions actually encompass all severe accidents. While the extreme accidents analyzed are rare, they are also expected to produce the greatest consequences.
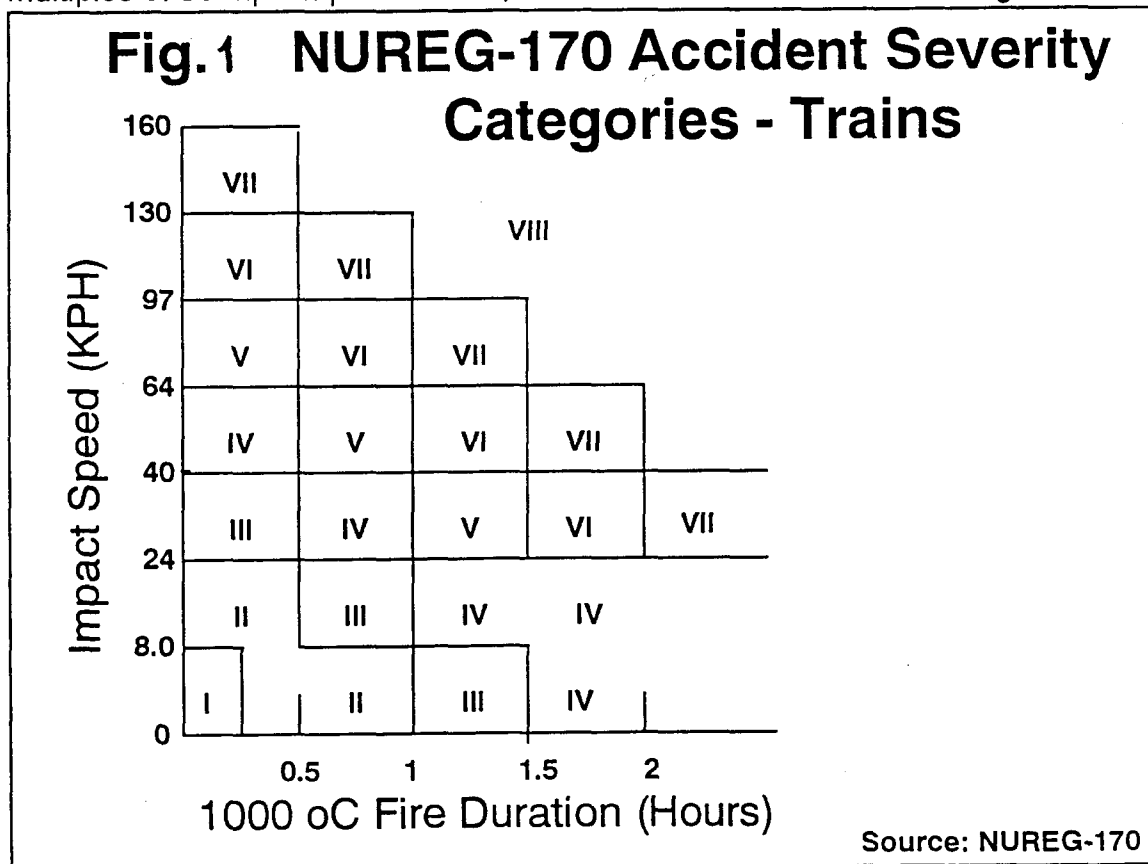
Shipping conditions anticipated by the Commission in 1977 have radically changed since that time. Contrary to Commission assumptions, without reprocessing or a federal repository, irradiated nuclear fuel has accumulated at reactors. With the loss of storage capacity in fuel pools, utilities have used higher burn up fuel and have begun to utilize dry storage casks. Storage conditions in dry storage casks are radically different from conditions in fuel pools. The maximum cladding temperature in dry storage casks is much hotter than in fuel pools. Extended fuel burnup and extended storage under high temperatures are expected to lead to a compromise in cladding integrity. These implications for the calculations of accident severity fractions and inputs to RADTRAN 4.1 are discussed in this report. Both the probability and consequences of severe accidents are expected to increase.

Finally, based on our review of extreme accidents and the assumptions underlying the accident severity calculations, we develop new accident severity fractions and a new range of inputs to be utilized in RADTRAN 4.1.

The results of this study raise questions about container response and the expected release of radioactive pollutants that are also important inputs to RADTRAN 4.1 and important contributors to the transportation risk. RADTRAN calculated the risk by summing up the probability times the consequences under the full range of accidents conditions. These important issues related to risk are discussed qualitatively in this report, but the focus is on the probability, not the consequences, of severe accidents.

NUREG-170

The question is, what are the appropriate parameters with which to classify all highway and rail accidents? In 1977, the Nuclear Regulatory Commission[1] in its environmental report on transportation of nuclear materials, developed a two-dimensional scheme which was transparently related to hypothetical accident conditions for Type B containers. These hypothetical accidents conditions are a 30 foot drop or 30 mph impact, a 1/2 hour fire at 1475 °F and a 40-inch drop onto a mild steel punch. The accident severity schemes is shown in Fig. 1 for trains. An identical scheme holds for trucks but is scaled at multiples of 30 mph impact and a 1/2 hour fire. The shaded area in Fig. 1

Fig. 1   NUREG-170 Accident Severity Categories - Trains

Impact Speed (KPH) vs 1000 oC Fire Duration (Hours)

VII				
VI	VII	VIII		
V	VI	VII		
IV	V	VI	VII	
III	IV	V	VI	VII
II	III	IV	IV	
I	II	III	IV	

Y-axis (Impact Speed KPH): 160, 130, 97, 64, 40, 24, 8.0, 0
X-axis (1000 oC Fire Duration Hours): 0.5, 1, 1.5, 2

Source: NUREG-170

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[1] Nuclear Regulatory Commission, *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes, Vol. 1*, December 1977.

corresponds to the impact and fire-duration region which a type B container is expected to withstand.

The classification scheme for trains employed in NUREG-170 is shown in Fig. 1. A similar plot exists for trucks. The accident severity scheme is a two-dimensional plot, impact velocity v. fire duration. Other parameters were available, such as puncture velocity, but the Commission decided that these two parameters in this particular array conveniently captured the spectrum of accidents, from minor to the extreme.

Note that an assumption is made here that all accidents in a particular category release the same amount of radioactivity. For example, according to Fig. 1, a fire between 1 1/2 and 2 hours without impact, accident severity category III, had the same severity as a cask impacting between 24 and 40 kph with no fire. Each of these accidents is expected to release the same amount of radioactivity. This equivalence between fire and impact had no technical foundation, but was simply asserted by the Commission.

Note also that while the accident severity schemes for trucks and trains is identical, though the impact velocity scale is much expanded for trains. Because of the much greater mass, impacts of the same velocity on the rails clearly can cause more serious accidents than trucks on the highway.

The expected release fractions for each accident severity are shown in Table 1, taken from NUREG-170. These had little technical basis except for the qualitative understanding that more severe accidents would have greater releases of radioactive material. The release percentages were correlated to the hypothetical accident conditions for type B containers. No physical model related the mechanical and thermal forces acting on a cask to fuel cladding, fuel and seal damage and thereby to the amount released. This is the fatal flaw in the NUREG-170 model that was corrected by Wilmot in 1981. But the values in Table 1 were conservatively chosen to bound any likely release.

Table 1. Release Fractions from Spent Fuel Cask

Severity	Release Fractions	
Category	Model I	Model II
I	0	0
II	0	0
III	1	0.01
IV	1	0.1
V	1	1
VI	1	1
VII	1	1
VIII	1	1

Source: NUREG-0170

Corresponding to each accident severity, the Nuclear Regulatory Commission proposed two models for the fraction of radioactive material released, as shown in Table 1. In Model I, no material was released in Categories I and II, and 100% for Categories III through VIII. In Model II, 1% of radioactive material is released in Category III, 10% in Category IV and 100% in Categories V through VIII. These percentages are for **available** gaseous and volatile materials. The definition of "available" further delimits the percentage of radioactive inventory that is actually projected to be released.

Nevertheless, using the severity scheme, it is theoretically possible to divide up the universe of real highway or rail accidents and assign a probability to each category. Unfortunately no single data base fully contains the information needed to classify accidents. The probability of accident severities is determined by breaking down accidents into different types: impact with a stationary object, impact with a train, head-on and rear-end collisions, single vehicle roll-over, and so on. The frequency of accident types is taken from the Bureau of Motor Carrier Safety data from the period 1968 to 1970. The data had to be recategorized into direct head-on, direct rear-end or direct side-on collisions. Sandia acknowledges that "this procedure necessitated subjective

judgment..." The BCMS data base did not specifically delineate truck velocities, The impact velocities were pre-accident speed distributions. Actual impact velocities are expected to be reduced by driver reaction prior to the accident, but the Sandia study did not take this matter into account. Since the BCMS data base did not include accident velocities, it was supplemented with data from Texas for December and April 1969. Unfortunately in the Texas data base, "trucks" included light pick-up trucks which have the mass of autos. The data base was therefore also supplemented with data from Alabama for the year 1970, but the Alabama data base included transport on two lane rural highways, not used for transportation of nuclear materials. Thus, none of the data bases was complete in itself.

In addition to the above deficiencies, three major drop accidents were not included in the Sandia analysis:

      1.   vehicles running off the road in mountainous terrain and dropping over a sheer cliff,
      2.   vehicles plunging off a high bridge over a bay or river and
      3.   vehicles falling over the side of an overpass.

Sandia could not evaluate the probability of any of these occurrences, but thought the probabilities "are extremely small."

In order to correlate real accident velocities with velocities into an unyielding surface, Sandia and the Nuclear Regulatory Commission calculated a relationship between yielding and unyielding surfaces. The theoretical basis for the calculation was Hertzian contact theory which we review in Appendix B. This theory allowed Sandia researchers to relate real accidents into real surfaces with hypothetical accidents conditions for type B casks into unyielding surfaces. As shown in the Appendix A, this theory required assumptions that do not hold for severe real accidents, namely, low speeds and elastic collisions. For severe accidents, the relationship developed in NUREG-170 is not expected to hold. A recent paper by Chen[2] confirms that the original Sandia relation between yielding and unyielding surfaces is non-conservative. As an aside, the relationship

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[2] Chen, TF, *et al*, "Impact Velocity vs. Target Hardness for Equivalent Response of Cask Structures," Lawrence Livermore National Laboratory, UCRL-JC-113750, June 1993.

between yielding and unyielding velocities as published in NUREG-170 and Sandia reports[3] is not correct. The correct relationship is shown in Appendix A.

To sum up national averages were used for impact accidents supplemented by limited State data from Texas and Alabama. Sandia did not estimate the probabilities of accident severities in specific population density zones. The earlier Sandia accident data base was supplemented with an additional analysis of 700 accidents by Dennis.[4]

Data sources for trains all come from the Federal Railroad Administration(FRA). For small containers data was taken from FRA 1972 and Class I freight trains from March to September 1973. For large containers the data was taken from the FRA between 1969-1972 and from the National Fire Protection Association in 1972.

For the fire environment, the BCMS data contained little information about fires, except whether a fire was associated with an accident. Fires were associated with 1% of all truck accident (4.4% of all fatal truck crashes). For accidents involving fires, 25% result from collision-type accidents. According to Sandia, fires occur in1.6% of train accidents. The database contained no information on the actual fire temperature and duration. Thus, for fires, Sandia assumed the flammable material was jet fuel and, employing a large number of assumptions, including the amount of petroleum available in an accident, the distance petroleum is likely to spread, the burn rate of the flammable materials, and so on, calculated fire durations. The lengthy list of assumptions is shown in Table 2. These basic parameters and assumptions were put into a Monte Carlo model which calculated the probability distributions for fire duration and temperatures. The calculated temperatures ranged from 1400 °F to 2400 °F. Sandia did not consider other flammables and the range of flammable temperatures. Below, we calculate the range of flammable temperatures for materials involved in 38 severe real accidents we examined in detail.

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[3] Clarke RK et al., *Severities of Transportation Accidents*, Sandia Laboratories, SLA-74-0001, July 1976.
[4] Dennis, AW, and JT Foley Jr, *Severities of Transportation Accidents Involving Large Packages*, SAND77-0001, May 1978.

Table 2. Assumptions Underlying Monte Carlo Calculations for Fire Temperature and Duration

1. Frequency of fire-accident types specified (fire only, fire and collision, fire and overturn, fire and ran off road, and fire and other noncollisions)
2. 99% of truck cargoes weigh between 0 - 20 tons; the average weight is 10 tons.
3. 50% of hazardous cargo shipments are composed of combustible materials.
4. All tanker shipments are flammable.
5. An average of 20% of the flammable cargo will burn.
6. Fuel tanks contribute to fire in a collison or overturn accident.
7. Fuel in the tank of a single-vehicle truck ranges from 0 - 200 gallons, uniform distribution over an area. Expected value is 120 gallons.
8. Fuel in a truck/auto collison ranges from 0 - 250 gallons with an expected value of 150 gallons.
9. Fuel in a truck/truck collision ranges from 0 - 500 gallons with an expected value of 300 gallons.
10. 2% chance in truck/truck collision that at least one is a tanker carrying flammble cargo.
11. Fuel in a truck/tanker collision ranges from 0 - 10,000 gallons with an expected value of 5,000 gallons.
12. Of noncollision fires: 30% occur in cargo; 10% in fuel system; 25% in tires, brakes, etc.; 15% in electrical system; 8% in cab; and 12% in other areas.
13. Of noncollision fires that originate in the cargo: 10% involve fuel; 100% involve combustible cargo.
14. Of noncollision fires that originate in the fuel system: 20% involve fuel tank; 10% involve combustible cargo. With neither involved, fire lasts between 0 - 10 minutes.
15. Of noncollision fires that originate in the tires, brakes, etc.: 10% involve fuel; 20% involve combustible cargo. With neither involved, fire lasts between 0 - 15 minutes.
16. Of noncollision fires that originate in the electrical system: 10 % involve fuel; 20% involve combustible cargo. With neither involved, fire lasts between 0 - 10 minutes.

17. Of noncollision fires that originate in the cab: 10% involve fuel; 20 % involve cargo. With neither involved, fire lasts between 0 - 20 minutes.
18. Of noncollision fires with unknown origins: 10 % involve fuel; 30 % involve cargo. With neither involved, fire lasts between 0 -15 minutes.
19. Burn rate of liquid hydrocarbon fuels equals 0.65 lb/ ft^2 min. corresponding to surface recession burn rate of 0.16 in/min.
20. Wood, ie cellulosic material, has 0.16 lb/ft^2.min burn rate for first 30 minutes; 0.09 lb/ft^2.min thereafter.
21. Combustible surface area ofnonliquid combustible cargo is 100 to 1000 ft^2, uniform distribution.
22. Char density of nonliquid combustible cargo is 35% of original density.
23. At scene of accident:
    30%, no fire-fighting capability;
    30%, local fire dept responds;
    10%, hand extinguisher used;
    30 % other fire-fighting efforts.
24. Hand extinguishers only effective against fires of less than 75 gallons of fuel or 100 lbs of combustible cargo; then fire controlled within 0 - 10 minutes.
25. Local fire departments are effective in all cases; fires controlled within 15 - 45 minutes.
26. Other firefighting efforts only effective against fires of more than 2000 gallons of fuel or 2500 lbs of combustible cargo. If effective, fire controlled within 5 - 30 minutes.
27. The fire is considered a blackbody radiation source with a flame thickness of 4 feet or more.

Source: Clarke RK et al., *Severities of Transportation Accidents*, Sandia Laboratories, SLA-74-0001, Vol III, July 1976.

The fractional occurrences calculated by Sandia were based on national accident statistics, that is, averaged over all states and all population density zones - rural, suburban and urban. The data was barely sufficient to calculate the fractional occurrences which appear in NUREG-170 (see Table 3 below) and had to be supplemented with Monte Carlo calculations. The data was clearly unavailable to further break down these fractional occurrences according to population density zone.

Despite the lack of technical basis, the Commission made educated guesses on proportioning the fractional occurrences according to population density zones. As seen in Tables 3 and 4, the least severe accidents, categories I and II, are assumed to occur in urban areas. Severe accidents, categories VI - VIII, are assumed to occur in rural areas, where truck velocities are higher. According to the Commission, "The table reflects a gradual shift of accidents to rural areas with increasing severity as average velocity increases." The Commission's rationale is based on impact speeds, but not on fire temperature and duration. The same bias toward impact is made for train accidents. These assumptions change the basic fractional occurrences by up to a factor of 20, but they have no quantitative basis. For the 38 severe accidents we investigated in detail, we have identified the population density zone and compared our results with the Commission's. These results are discussed later.

Given the fractional occurrences and the fractional occurrences according to population density zones, we calculate the inputs to RADTRAN II and RADTRAN IV in Table 5a, 5b and 6a , 6b for trains and trucks, respectively. The results are identical to those that appear in RADTRAN II and RADTRAN IV.

Sandia 1981

In 1981, Sandia researchers attempted to resolve the weakest feature of the above accident analysis, the lack of a physical model to estimate the release of radioactive materials in a severe accident. A fault-tree model[5] was developed to estimate releases from spent fuel to the cask and from the cask into the outer

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[5] Wilmot, EL, *Transportation Accident Scenarios for Commercial Spent Fuel*, Sandia National Laboratories, SAND80-2124, February 1981.

Table 3. Fractional Occurrences For Truck Accidents By Accident Severity Category And Population Density Zone

Accident Severity Category	Fractional Occurrences	Fractional Occurrences By Population Density Zones		
		Low	Medium	High
I	.55	.1	.1	.8
II	.36	.1	.1	.8
III	.07	.3	.4	.3
IV	.016	.3	.4	.3
V	.0028	.5	.3	.2
VI	.0011	.7	.2	.1
VII	8.5×10^{-5}	.8	.1	.1
VIII	1.5×10^{-5}	.9	.05	.05

*Overall Accident Rate = 1.06×10^{-6} accident/kilometer
Source: Table 5-3, NUREG-0170

Table 4. Fractional Occurrences For Train Accidents By Accident Severity Category And Population Density Zone

Accident Severity Category	Fractional Occurrences	Fractional Occurrences By Population Density Zones		
		Low	Medium	High
I	.50	.1	.1	.8
II	.30	.1	.1	.8
III	.18	.3	.4	.3
IV	.018	.3	.4	.3
V	.0018	.5	.3	.2
VI	1.3×10^{-4}	.7	.2	.1
VII	6.0×10^{-5}	.8	.1	.1
VIII	1.0×10^{-5}	.9	.05	.05

*Overall Accident Rate = 0.93×10^{-6} railcar accident/railcar-kilometer.
Source: Table 5-5, NUREG-0170

Table 5a. Accident Severity by Population Density Zone
Eight Severity Category Scheme - Train

NUREG-170 Accident Severity Fractional Occurrences

0.5	0.3	0.18	0.018	0.0018	0.00013	6E-05	1E-05	1

Multiply NUREG-170 accident severity fractional occurrences by overall accident rate,
9.3E-7 railcar-accidents/railcar-km and fractional occurrences by population zone:

	I	II	III	IV	V	VI	VII	VIII
rural	0.1	0.1	0.3	0.3	0.5	0.7	0.8	0.9
suburban	0.1	0.1	0.4	0.4	0.3	0.2	0.1	0.05
urban	0.8	0.8	0.3	0.3	0.2	0.1	0.1	0.05

Train	I	II	III	IV	V	VI	VII	VIII	
rural	4.7E-08	2.8E-08	5E-08	5E-09	8.4E-10	8.463E-11	4.5E-11	8.37E-12	1.3E-07
suburban	4.7E-08	2.8E-08	6.7E-08	6.7E-09	5E-10	2.418E-11	5.6E-12	4.65E-13	1.5E-07
urban	3.7E-07	2.2E-07	5E-08	5E-09	3.3E-10	1.209E-11	5.6E-12	4.65E-13	6.5E-07

Divide each line by accident rate in each population density zone and normalize each row so that
the sum of accident severity fractions in each population density zone is 1.

RADTRAN IV Inputs

Train	I	II	III	IV	V	VI	VII	VIII
rural	0.356004	0.213602	0.384484	0.038448	0.006408	0.0006479	0.000342	6.408E-05
suburban	0.312945	0.187767	0.450641	0.045064	0.00338	0.0001627	3.8E-05	3.129E-06
urban	0.571609	0.342965	0.077167	0.007717	0.000514	1.858E-05	8.6E-06	7.145E-07

Table 5b. Accident Severity by Population Density Zone Six Severity Category Scheme - Train

SAND80-2124 Accident Severity Fractional Occurrences

0.604	0.395	0.001	1E-06	1E-06	1E-06

9.3E-07 railcar-accidents/railcar-km

Multiply SAND80-2124 accident severity fractional occurrences by overall accident rate, 9.3E-7 railcar-accidents/railcar-km and fractional occurrences by population zone:

	I	II	III	IV	V	VI
rural	0.1	0.1	0.3	0.3	0.5	0.7
suburban	0.1	0.1	0.4	0.4	0.3	0.2
urban	0.8	0.8	0.3	0.3	0.2	0.1

Train	I	II	III	IV	V	VI
rural	5.6E-08	3.7E-08	2.8E-10	2.8E-13	4.7E-13	6.51E-13
suburban	5.6E-08	3.7E-08	3.7E-10	3.7E-13	2.8E-13	1.86E-13
urban	4.5E-07	2.9E-07	2.8E-10	2.8E-13	1.9E-13	9.3E-14

Divide each line by accident rate in each population density zone (shown below).

Train	I	II	III	IV	V	VI	
rural	0.56172	0.36735	0.00279	2.8E-06	4.7E-06	6.51E-06	0.931874
suburban	0.029564	0.019334	0.000196	2E-07	1.5E-07	9.789E-08	0.049095
urban	0.029958	0.019592	1.9E-05	1.9E-08	1.2E-08	6.2E-09	0.049569

accident rates

rural	1E-07
suburban	1.9E-06
urban	1.5E-05

Normalize each row so that sum of accident severity fractions in each population density zone is 1.

RADTRAN IV Inputs

Train	I	II	III	IV	V	VI
rural	0.602785	0.394206	0.002994	3E-06	5E-06	6.986E-06
suburban	0.602188	0.393815	0.003988	4E-06	3E-06	1.994E-06
urban	0.604377	0.395247	0.000375	3.8E-07	2.5E-07	1.251E-07

Table 6a. Accident Severity by Population Density Zone
Eight Severity Category Scheme - Truck

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NUREG-170 Accident Severity Fractional Occurrences

| 0.55 | 0.36 | 0.07 | 0.016 | 0.0028 | 0.0011 | 8.5E-05 | 1.5E-05 |

Multiply NUREG-170 accident severity fractional occurrences by overall accident rate, 1.06 E-6 accidents/km and fractional occurrences by population zone:

	I	II	III	IV	V	VI	VII	VIII
rural	0.1	0.1	0.3	0.3	0.5	0.7	0.8	0.9
suburban	0.1	0.1	0.4	0.4	0.3	0.2	0.1	0.05
urban	0.8	0.8	0.3	0.3	0.2	0.1	0.1	0.05

Truck	I	II	III	IV	V	VI	VII	VIII
rural	5.83E-08	3.816E-08	2.226E-08	5.088E-09	1.484E-09	8.162E-10	7.208E-11	1.431E-11
suburban	5.83E-08	3.816E-08	2.968E-08	6.784E-09	8.904E-10	2.332E-10	9.01E-12	7.95E-13
urban	4.66E-07	3.053E-07	2.226E-08	5.088E-09	5.936E-10	1.166E-10	9.01E-12	7.95E-13

Divide each line by accident rate in each population zone (shown below).

rural	4.158E-01	2.722E-01	1.588E-01	3.629E-02	1.058E-02	5.822E-03	5.141E-04	1.021E-04	0.900104
suburban	2.175E-02	1.423E-02	1.107E-02	2.530E-03	3.321E-04	8.698E-05	3.361E-06	2.965E-07	0.050003
urban	2.917E-02	1.909E-02	1.392E-03	3.182E-04	3.712E-05	7.292E-06	5.635E-07	4.972E-08	0.050016

Normalize each row so that sum of accident severity fractions in each population density zone is 1.

RADTRAN IV Inputs

Truck	I	II	III	IV	V	VI	VII	VIII
rural	0.4619849	0.3023901	0.1763942	0.0403187	0.0117596	0.0064678	0.0005712	0.0001134
suburban	0.4348883	0.2846542	0.2213977	0.0506052	0.0066419	0.0017396	6.721E-05	5.93E-06
urban	0.5831837	0.3817202	0.0278338	0.006362	0.0007422	0.0001458	1.127E-05	9.941E-07

Rural acct rate	1.402E-07
Suburban acct rate	2.681E-06
Urban acct rate	1.599E-05

Table 6b. Accident Severity by Population Density Zone
Six Severity Category Scheme - Truck

SAND80-2124 Accident Severity Fractional Occurrences

0.604	0.395	0.001	1E-06	1E-06	1E-06

1.06E-06 accts/km

Multiply SAND80-2124 accident severity fractional occurrences by overall accident rate, 1.06E-6 accidents/km and fractional occurrences by population zone:

	I	II	III	IV	V	VI
rural	0.1	0.1	0.3	0.3	0.5	0.7
suburban	0.1	0.1	0.4	0.4	0.3	0.2
urban	0.8	0.8	0.3	0.3	0.2	0.1

Truck	I	II	III	IV	V	VI
rural	6.4E-08	4.187E-08	3.18E-10	3.18E-13	5.3E-13	7.42E-13
suburban	6.4E-08	4.187E-08	4.24E-10	4.24E-13	3.18E-13	2.12E-13
urban	5.12E-07	3.35E-07	3.18E-10	3.18E-13	2.12E-13	1.06E-13

Divide each line by accident rate in each population zone (shown below).

Truck	I	II	III	IV	V	VI	
rural	3.0780769	2.0129808	0.0152885	1.529E-05	2.548E-05	3.567E-05	5.1064226
suburban	0.1576946	0.1031281	0.0010443	1.044E-06	7.833E-07	5.222E-07	0.2618693
urban	0.2188855	0.1431453	0.0001359	1.359E-07	9.06E-08	4.53E-08	0.3621669

accident rates
rural	2.08E-08
suburban	4.06E-07
urban	2.34E-06

Normalize each row so that sum of accident severity f4ractions in each population density zone is 1.

RADTRAN IV Inputs

Truck	I	II	III	IV	V	VI
rural	0.6027854	0.3942057	0.002994	2.994E-06	4.99E-06	6.986E-06
suburban	0.602188	0.393815	0.003988	3.988E-06	2.991E-06	1.994E-06
urban	0.6043773	0.3952467	0.0003752	3.752E-07	2.502E-07	1.251E-07

environment. Sandia researchers estimated the failure of cask components under specific accident conditions. The different accident severity categories were divided into six classes. Categories I and II, which do not lead to a release of radioactive materials in the fault-tree approach, were equivalent to the first two categories in NUREG-0170. Category 3 corresponded to an impact greater than the regulatory drop test, severe enough to damage the cask seals and to spall crud from the exterior of spent fuel. Category 4 corresponded to an impact sufficient to damage the cask seals and create cracks or splits in spent fuel cladding. Under a Category 4 accident, gases and volatiles would enter the cask cavity. A Category 5 accident would involve forces severe enough to damage the cask seals and be accompanied by a fire severe enough to cause burst rupture of the fuel rods. A Category 6 accident would involve fuel oxidation, in which fuel oxidized from UO_2 to U_3O_8. This oxidation would cause fuel expansion and particulates would also be released from the cask.

While the physical model was improved with this fault-tree analysis, the probability estimates for these severe accidents were still based on the probability estimates made earlier in 1977 by Dennis[6] and others. A mere three pages are devoted to determining the accident rates and probabilities. The analysis assumed that fire and impact are independent variables. The probability of the most severe impact and fire accident was obtained by multiplying the probability of the most severe impact accident by the probability of the most severe fire accident. This is a major error since the impact and fire parameters are not independent. The joint probability of severe impact and severe fire is not the simple product of the individual probabilities. In the BCMS data employed, 1% of truck fires (for 1990, 4.4% of fires are associated with fatal crashes) are correlated with an impact (fires may also occur without impact). The probabilities of severe accidents in each most severe category are then multiplied by the accident rate and the number of truck miles to determine that a Category 6 accident would occur once in a million years. Thus, while the physical model was improved with the 1981 Sandia analysis, the joint probability estimates were not properly calculated. These probability estimates are discussed in more detail below.

The same fractional occurrences by population density zone that were employed in NUREG-170 were used to unfold the Wilmot fractional occurrences,

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[6] Dennis, AW, and JT Foley Jr, Severities of Transportation Accidents Involving Large Packages, SAND77-0001, May 1978.

except that the most severe categories, VII and VIII, were not employed. Just as with the 8-category accident severity scheme, there is no technical basis for these probability estimates, and especially for truncating categories VII and VIII to accommodate the 6-category scheme. No technical reports by Sandia discuss these fractional occurrences by population density zones. Further, as we discuss below, these fractional occurrences by population density zones do not square with reality. The spreadsheet calculations are shown in Table 5b and 6b for trains and trucks respectively. Note that the 8-severity category fractional occurrences by population zone must be arbitrarily truncated to 6 categories. The calculated values in Tables 5b and 6b are identical to those employed in RADTRAN IV.

Fischer 1991

The correlation between accident severity probabilities and cask damage was tightened with later analysis by Fischer[7]. As discussed above, the relationship between the thermal environment, mechanical forces and the accident severity scheme developed in NUREG-0170 was somewhat arbitrary and not well formulated. The fault-tree method developed by Wilmot, based on the failure of cask components and fuel, improved the correlation between the accident environment and releases of radioactive materials from the cask. But the probability of such events, that is, the probability of specific category accidents, was qualitative. Fischer attempted to tie together the accident environment with radioactive releases. Rather than the thermal and mechanical forces on a cask, he chose as parameters the response of the cask to these forces.

The Modal Study employed two parameters to describe the cask response to the mechanical and thermal forces on a cask in an accident: strain and temperature. For the thermal response parameter, Fischer chose the temperature at the middle of the lead shield thickness. For the cask response to mechanical forces on a cask, he chose the parameter, strain or elongation of the

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[7] Fischer, LE, *et al, Shipping Container Response to Severe Highway and Rail Accident Conditions: Main Report (Technical Report)*, Lawrence Livermore National Laboratory, NUREG/CR-4829-v1, February 1987 and

  Fischer, LE, *et al, Shipping Container Response to Severe Highway and Rail Accident Conditions: Appendices (Technical Report)*, Lawrence Livermore National Laboratory, NUREG/CR-4829-v2, February 1987.

inner metal shell. Fischer then proceeded to examine real severe forces which have occurred on the highway and rail, employing data previously developed by Eggers[8], to determine the response of a cask to these extreme forces.

Rather than the somewhat arbitrary 1/2 hour temperature divisions, Fischer chose the following temperature divisions in the accident severity scheme:

T1 = 500 °F, a temperature below the melting point of lead, 621 °F. This is a region of constant phase for lead.
T2 = 600 °F, also a region of constant phase, but near the lead melting point
T3 = 650 °F, above the melting point of lead, where the lead volume has expanded 10% and the seals are expected to leak
T4 = 1050 °F.

It is important to recognize that a large heat input is needed to melt lead, to raise the lead temperature from T2 (600 °F) to T3 (650 °F). As we discuss below, newer generation casks, however, will probably not contain lead since they will be designed to hold more fuel, after aging 5 to 10 years. Lead is employed as a gamma attenuator. But since lead will push the weight of the cask above standard highway weight limits (40 tons) into the overweight region that necessitates State overweight permits, cask manufacturers will probably use depleted uranium. The above temperature categorization scheme will then not be as useful for the newer generation casks.

Further, Fischer chose an external water jacket neutron absorber for his standard model cask. This choice is also not appropriate for newer generation casks which use borated plastic neutron absorbers. The water jacket, assumed to be dry in severe fires or impacts, serves as an air space thermal insulator. Without this thermal insulator and lead, the cask would be expected to heat up more rapidly in a high temperature, long duration fire.

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[8] Eggers, P, *Severe Rail and Truck Accidents: Toward a Definition of Bunding Environments for Transportation Packages,* prepared for Nuclear Regulatory Commission, NUREG/CR-3499, October 1983.

To understand the differences between a lead-lined and depleted uranium lined cask, one can compare the Fischer cask with the General Electric IF300 Irradiated Fuel Shipping Cask. The General Electric IF 300 cask is a depleted uranium shielded and stainless steel clad, annular cylinder. The temperature within the IF-300 continues to increase with additional heat input. The parameters of the fire analysis are: 1475°F the flame temperature, 30 minute fire duration, 0.9 environmental emissivity and 0.8 cask absorption coefficient.[9] At the end of the fire the cask inner cavity temperature is 355°F (originally 285°F), the cask body is 457°F (originally 238°F) and the maximum fuel pin temperature is 385°F (originally 326°F).[10]

The temperature of the inner cavity of the Fischer truck cask does not rise continuously with heat input because the lead melting temperature is at a low 621 °F. Fig. 2 shows the rise of cavity temperature with heat input, illustrating a constant cavity temperature for an hour or so until the temperatures again rise. The Fischer study examined the cavity temperatures while the heat input continued, but the cavity temperature would continue to rise after the heat input ceased because the fuel and lead would continue to contribute to rising temperatures for some time after the heat input ceased.

For the cask response to impact forces, Fischer chose the parameter strain at the inner shell of the cask structure and the following strain divisions in the accident severity scheme:

S1 = 0.2% strain at the inner shell. This corresponds to less than a 40g axial force and an elastic cask response. At these forces, within the type A container regulatory limits, there is no lead slump.
S2 = 2% plastic strain at the inner shell. At these forces, within the type B container regulatory limits, there is some lead slump and up to 10% of the fuel rods leak.
S3 = 30% strain at the inner shell. This is below the fracture strain of 304 stainless steel. At these forces, cracking at cask welds and seal leakage is expected.

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[9] GE-Safety Analysis Report, pg.2-12.
[10] GE-SAR report; Table VI-2, pg. 6-3 and Table VI-5, pg.6-10.

The strain was defined at the inner wall of the cask, not the outer wall, the end closure, or other vulnerable areas of the cask. Further, the cask structure was simplified and altered to facilitate analysis under different accident conditions. Fischer assumed that the bolted cask end closure was structurally resistant to mechanically imposed impacts. Two other assumptions were made by Fischer. The closure bolts were assumed to be designed with enough strength to function from corner or end drops of the cask. The design of the cask, it was assumed, will provide significant protection against impacts that could compromise the large diameter bolts that secure the end closure. For these reasons the specific closure of the cask was neglected in the representative cask design.

Fig. 2:Temperature VS. Fire Duration

Modal Truck Cask
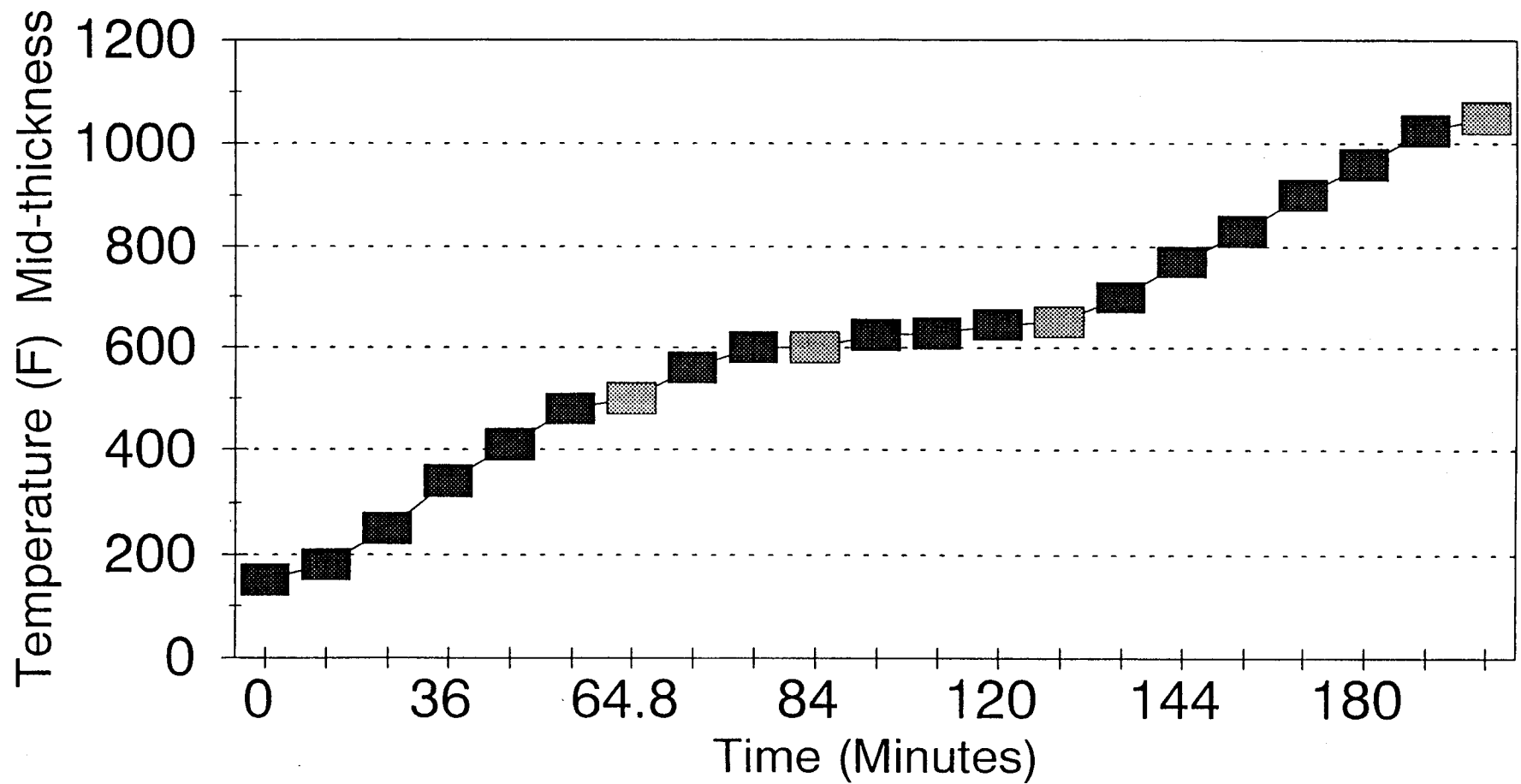
The subsystems were not included because the valves and pipes are within the cask body and all exterior valves are assumed to be protected by the impact limiter. Finally, the Fischer model does not represent the type of casks presently being considered by the Department of Energy, the MPC system, in which a **welded** inner closure will replace a bolted closure.
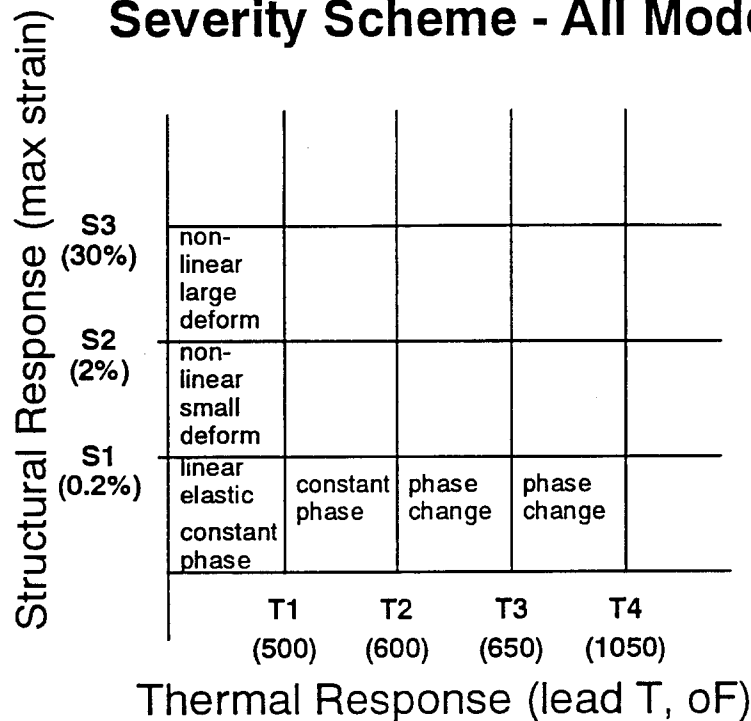
The need to model the end closures can be illustrated by the Sandia full-scale tests. For the first (less severe) test the cask had a velocity of 27 mph when the cab was crushed solid. The cask remained intact with only minor damage to external features. Some external piping near the front end as well as some of the cooling fins were damaged. The head bolt tightness was found loosened somewhat; however, no leakage occurred. For the second test the cask encountered a hard target at 62 mph. There was radial cracking of some of the cooling fins in the front and there was 100 cc seepage of coolant. In the more severe full size test the cask body shortened 1.6%(6 cm). This indicates that the fuel could have been damaged at a 62 mph collision.

Employing these parameters, the Modal Study accident severity scheme is shown in Figure 3. The scheme has 20 accident severity categories. According to Fischer[11], almost all accidents (99.4%) fit within the least severe category and 0.6% fit within the next severe category, another reason why the scheme is not particularly appropriate for accident analysis. Fischer employed the same method of analysis as Dennis, but used more complete data bases, including data from California.

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[11] Fischer, p. 6-45 and 7-1.

Fig. 3 Modal Study Accident Severity Scheme - All Modes

Structural Response (max strain)	Thermal Response (lead T, oF)			
S3 (30%)	non-linear large deform			
S2 (2%)	non-linear small deform			
S1 (0.2%)	linear elastic constant phase	constant phase	phase change	phase change
	T1 (500)	T2 (600)	T3 (650)	T4 (1050)

Review of Severe Accidents

Location of Severe Accidents

The location of severe accidents, that is, fractional occurrences according to population zones, was historically based on impact only. Higher speed impacts were assumed to occur in rural areas; low speed impacts in urban areas. The NUREG-170 analysis was qualitative and based solely on impact; no technical basis was presented. The Commission's reasoning was not based on data on severe fires accidents. Unfortunately, BCMS highway data and FRA rail data do not list the population density of accident locations. Short of analyzing a data base of thousands of accidents, breaking these down into accident severity categories and population density zones, we analyze the 38 extra severe accidents in the Appendix by population density zone.

Analysis of the data base in the Appendix shows that for trains, most high speed impacts occur at downgrades, particularly if curves are present. Downgrades are as likely in suburban as rural areas. For trains, long downgrades, particularly for over-capacity loads, cause brake burn-out and loss of braking ability. Hot brakes cause fires. For rail accidents, many long duration fires have occurred in suburban areas, particularly on lines carrying combustible materials. Again these fires often occur near downgrades and curves which are not necessarily located in rural areas.

Analysis of the 38 severe accidents, categories VI - VIII, are shown in Tables 7 and 8 for highways and rails, respectively. Contrary to the Commission's conclusions in NUREG-170, most extra severe highway and rail accidents occur in suburban areas, not in rural areas. This change is due to our inclusion of high temperature, long-duration fires. For truck accidents, we have 2, 10 and 7 accidents in rural, suburban and urban areas, respectively. That is, 11% of extra severe accidents occur in rural areas, 53% in suburban areas and 36% in urban areas. Thus, for the 8-accident severity classification scheme for trucks, we take as rural, suburban and urban accident severity fractions for category VIII accidents, 0.11, 0.53 and 0.36, and adjust the remaining fractions accordingly.

For trains, the extra severe accident data base has 6, 10 and 5 accidents in rural, suburban and urban population density zones, respectively. That is, for trains, we take as rural, suburban and urban accident severity fractions 0.29, 0.48 and 0.24 for category VIII accidents and adjust the remaining fractions accordingly.

Our revised fractional occurrences by population density zones are shown in Tables 9 and 10, for trucks and trains, respectively.

For the 6-accident severity classification scheme, we simply truncate categories VII and VIII, as Sandia has done for inputs to RADTRAN IV. For Fischer's 20-accident severity scheme, neither he nor we have partitioned the accidents according to population density zones.

Impact - drops

As stated earlier, three major accidents involving falls from bridges or heights were not included in the Sandia analysis because Sandia considered the probabilities "extremely small." Six of 38 severe accidents we analyzed involved falls from heights. Clearly, once in free fall, no braking or evasive actions are possible, unlike other highway accidents. The regulatory requirement for a type B cask is a 30 foot drop or a 30 mph crash into an unyielding surface. As seen in Table 11, the terminal velocities ranged between 53 mph and 71 mph.

The surfaces underneath the bridges ranged from water to sand to rock. Thus, several of these accidents, particularly into rock, would likely have exceeded regulatory requirements. Including such severe accidents would increase the probability of severe impacts.

Nor were other types of loadings on casks considered by Sandia and Lawrence Livermore researchers. For example, in the Loma Prieta 1988 earthquake the upper roadway fell onto lower roadway, causing massive crush forces amounting to 740,000 tons. The maximum crush forces considered by Fischer/Eggers is 100 tons (railroad) and 30 tons (highway). Thus, this

Table 7. Location of Severe Truck Accidents

Location	Rural	Suburban	Urban
Carrsville, Virgina		X	
near Mobile, Alabama		X	
near Amsterdam, New York		X	
near Covington, Tennessee		X	
near Greenwich, Connecticut		X	
Checotah, Oklahoma		X	
Wenatchee, Washington			X
near Yardley, Pennsylvania*		X	
near Waco, Georgia	X		
Lynchburg, Virginia			X
Springfield, Massachusetts			X
Braintree, Massachusetts		X	
Sacramento, California			X
Nashville, Tennessee			X
Point Pleasant, West Virginia		X	
Brooklyn, New York			X
Oakland, California			X
Waynesville, North Carolina		X	
Sound View , Connecticut *	X	X	
Total	**2**	**10**	**7**

* Repeated in both truck and train listings

Table 8. Location of Severe Train Accidents

Location	Rural	Suburban	Urban
Crestview, Florida		X	
Muldraugh, Kentucky		X	
Thermal ,California	X		
Livingston, Louisiana	X		
Baton Rouge, Louisiana			X
Denver, Colorado			X
near Pine Bluff, Arkansas		X	
Helena, Montana			X
Benson, Arizona		X	
San Bernardino, California			X
near Freeland, Michigan		X	
Laurel, Mississippi			X
Crete, Nebraska		X	
Cresent City, Illinois		X	
near Des Moines, Iowa		X	
Lewisville, Arkansas	X		
Waverly, Tennessee	X		
near Yardley, Pennsylvania*		X	
Roseville, California		X	
near Pettisville, Ohio ???			
Sound View, Connecticut *	X		
Total	**6**	**10**	**5**

Table 9. Revised Fractional Occurrences For Truck Accidents By Population Density Zone

Accident Severity Category	Fractional Occurrences By Population Density Zones		
	Low	Medium	High
I	.1	.1	.8
II	.1	.1	.8
III	.3	.4	.3
IV	.3	.4	.3
V	.3	.4	.3
VI	.3	.4	.3
VII	.15	.5	.35
VIII	.11	.53	.36

*Overall Accident Rate = 1.06 x 10^{-6} accident/kilometer

Table 10. Revised Fractional Occurrences For Train Accidents By Population Density Zone

Accident Severity Category	Fractional Occurrences By Population Density Zones		
	Low	Medium	High
I	.1	.1	.8
II	.1	.1	.8
III	.3	.4	.3
IV	.3	.4	.3
V	.3	.4	.3
VI	.3	.4	.3
VII	.3	.45	.25
VIII	.29	.48	.24

*Overall Accident Rate = 0.93 x10^{-6} railcar accident/railcar-kilometer.

Table 11. Terminal Velocities: Truck Falls from Bridges

ID Number	Accidents with Fall	Horizontal Velocity (Vx) (mph)	Vertical Velocity (Vy) (mph)	$V = \sqrt{(V_x)^2 + (V_y)^2}$
NTSB-RAR-86-01	Collapse of the US 43 Chickasawbogue Bridge	40	*	
NTSB-HAR-88-02	Collapse of the New York Thruway	45	48.9	66.454570
	Bridge over Walnut Creek in Chatauqua County	45	54.7	70.831420
NTSB-HAR-90-01	Collapse of the Northbound US Rte 51 Bridge	50	*	500
NTSB-HAR-84-03	Collapse of Interstate Route 95 Highway Bridge	50	45.8	67.80590
NTSB-HAR-74-2	Crash off the Silliman Evans Bridge, I-24/65	30	44.1	53.336760
NTSB-SS-H-2	Collapse of US 35 Highway Bridge	40	*	40

* Bridge heights were not specified.

earthquake in Oakland, California, with forces 27,000 times greater, would likely have damaged a shipping cask.

Several rail accidents involving explosives and exploding tanker cars would have caused major puncture environments. A rail accident in Helena, Montana that was followed by a long duration fire caused 90-ton tanker cars to fly over 1/4 mile. Such impact forces were not evaluated by Sandia/LLNL researchers in estimating accident severity factors.

Other accidents have produced massive explosive forces. For example, an explosion of 18 boxcars, each containing 44 tons of 250-lb bombs in Roseville, California in 1973 totally leveled a circular area 1 1/4 miles in radius. While the probability of such a severe accident is rare, explosive forces causing extreme puncture environments have also not been incorporated into accident severity calculations.

fire duration, temperature

Fires occur in approximately 1.6 percent of all truck accidents. For severe accidents, involving fatalities, fires occur in 4.4 % of all fatal crashes.[12]

In the Sandia studies, the fire duration and temperature were not derived from actual accident data because the fire data did not exist. Rather, Sandia constructed a range of assumptions, shown in Table 12 which allowed Sandia researchers to calculate a range of temperatures for possible highway and rail fires. The calculated range was 1400 °F to 2400 °F. As seen in Table 12, these assumptions involved the type of flammable materials, the extent of fuel spread in an accident, the burn rate of spread fuel, and so on. However, a large variety of flammable materials were not included. For the accident data base in the Appendix, we have identified all flammable materials involved in severe accidents and have calculated the flame temperatures. These calculations appear in Appendix B.

In order to determine the range of flame temperatures, a simple and basic procedure was used. The range represents the lower to upper flammibility limit of each burned material. The flammability limits are "the composition limits

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[12] Fatal Accident Reporting System 1990, National Highway Traffic Safety Administration, US DOT, Washington, D.C., p. 108, Table 5.

within which a flame can propagate and are expressed as concentrations of the fuel in a specific oxidant /dilutant mixture at a specific temperature and pressure. As can be seen by Table 12, this range of flame temperatures are given for the corresponding flammibility limits. The two lists of flame temperatures correspond to heat capacities at 727°C and at 25°C (room temperature) respectively. The procedure in solving these flame temperatures is best explained by giving an example of a common chemical (i.e. acetone), performed in Appendix B.

These calculations for both lower and upper flammability limit are contingent on some assumptions. Primarily it is assumed that there is as much oxygen as needed in the air. This is important at the upper flammability limit since the amount of oxygen necessary to balance the chemical reaction is deficient in reactants. It was then presumed that an unlimited supply of oxygen was available. The more oxygen that is available, the higher the flame temperature will rise. Therefore the range given in the table spans the range from just enough oxygen to cause a fire to an unlimited supply of oxygen.[13] The range of fire temperatures is given in Table 12. As seen, the temperatures arnged from a low of T ≈ 1000 °C to T > 6000 °C. That is, the range of temperatures greatly exceeds the regulatory limit, 800 °C (1475 °F) for an all-engulfing fire.

Numerous examples of railroad high-temperature long-duration fires are discussed in the Appendix. The basic problem is that Sandia researchers could not foresee all possible accident conditions. As one example, in estimating fire duration probabilities, Sandia did not anticipate the fact that pipelines transporting gasoline can co-exist along the same right-of-way with rail tracks and that a train accident could be correlated with a pipeline explosion, such as occurred in 1989 in San Bernardino, California. As another example, Sandia assumed that in an accident involving a gasoline tanker would be spread over 200 square feet and burn at a constant rate. But in the Caldecott Tunnel fire in Oakland, California in April, 1983, gasoline remained in one location and was fed by air like a blowtorch. This caused a highly localized, all-engulfing, high temperature fire for over 2 hours. For up to 40 minutes, the temperatures exceeded 1900 °F. The probability of such a severe fire, according to Sandia researchers, was essentially infinitesimal.

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[13]Note: All calculation procedures were taken from; *The SFPE Handbook of Fire Protection Engineering,* National Fire Protection Association, Quincy ,MA, 1988.

Table 12. Flame Temperature Calculation

Materials Burned	Number of Accidents	Flammability Limit (% of volume)	Flame Temp (oC)*	Flame Temp (oC)**
Acetone	2	2-13	1183-3911	1472-4904
Acrylic Acid	1	3-	1198-	1404-
Acrylonitrile	1	3-16	1591-5096	1919-6457
Butyl Acrylate	1	2-10	1537-3776	1808-4753
Carbolic Acid	1	1.8-	1584-	1868-
Carbon Tetrachloride	1			
Chlorine	2			
Diesel Fuel		------		949-1004*
Gasoline (Octane)	6	1.4-7.6	2046-4884	2416-6221
Hydrogen Peroxide	1			
Isopropyl Alcohol	1	2-13	1161-4025	1323-5032
Liquified Petroleum Gas (LPG)-mostly C3H8	2	2.1-	1218-	1415-
Liquified Petroleum	2		-----	
Methyl Alcohol	1	6-36	1107-3505	1392-4403
Petroleum Naptha	1		1-6	
Propane	2	2-10	1228-3586	1427-4422
Sodium Nitrate	1			
Styrene Monomer	2	1-6	1386-4434	1619-5623
Synthetic Plastic (Polymethylene polyphylisocyanate)	1			
Toluene Diisocyanate	1	1-10	998-4316	1161-6840
Trimethylchlorosilane	1		-----	
Vinyl Chloride	3	3-33		1400-6172
Vinyl Chloride Monomer	1			

*Flame temperature with the heat capacity at 727 C.

**Flame temperature with the heat capacity at 25 C.

Note: All heat of combustion come from the "Handbook of Chemistry and Physics"

except Acetone, Methanol, Propane, LPG, Acrylic acid, Butyl Acrylate and Vinyl Cloride.

Acetone, Methanol, propane and LPG come from "The SFPE Handbook of Fire Protection Engineering".

Acrylic Acid, Butyl Acrylate and Vinyl Chloride come from "Physical & Thermodynamic Properties of

Pure Chemicals" by T.E. Daubert and R.R. Danner.

At-Reactor Storage and Transportation Safety

Several issues inherent to high burnup fuel and dry cask storage were never anticipated by the Nuclear Regulatory Commission at the time NUREG-0170, the environmental statement on nuclear transportation, was prepared. These issues involve embrittlement of fuel cladding and creep corrosion cracking.

Because of the lack of a high-level waste repository and reprocessing, utilities have had to store nuclear fuel in fuel pools which are nearing or exceeding capacity. Of 114 power reactors, as many as 26 reactors will require dry storage by the year 2000. The lack of an off-site location for irradiated fuel has led utilities to use higher enriched fuel which led to higher burnups. In addition, some older reactors, such as Palisades are using fuel as a neutron absorber to slow the embrittlement of aging reactors. The effect of higher burnup has been that fuel cladding has become brittle. At the Palisades reactor, a fuel rod that had already gone through five fuel cycles shattered. If such fuel were transported, it is likely that fuel rods would shatter in the course of a severe transportation accident. As a consequence of fuel cladding embrittlement, both the probability and the consequences of severe transportation accidents needs to be re-evaluated.

Two recent papers have discussed these issues in qualitative terms. A paper by Sandia[14] discussed slow crack growth which would release contained gases, thereby reducing cladding stresses from internal pressurization. The Sandia paper concluded that integrity of fuel cladding would be maintained if the storage temperatures were maintained sufficiently low.

The basic problem here is that little information is available on cladding integrity under long-term dry storage conditions. Added to this lack of information is the possibility that dry storage casks may not be opened before

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[14] P McConnell, *et al*, "Issues Related to the Transport of a Transportable Storage Cask After Storage," in *Proceedings of the Third International Conference, High-Level Radioactive Waste Management*, Las Vegas, Nevada, April 12-16, 1992, American Nuclear Society, pp.1174.

shipment, so that the cladding may not be inspected. Besides, 2,300 assemblies already have failed or damaged fuel rods, even before long-term storage.[15]

Extended storage in dry casks is not the same as extended storage in fuel pools, the practice anticipated by NUREG-0170. The cladding temperatures are much hotter, placing the cladding under continual stress. This is particularly true for the concrete casks, such as the NUHOMS or VSC-24, which operate at much higher temperatures than metal casks. Creep corrosion cracking is possible and this in turn increases the likelihood of impact and burst rupture in a severe accident. These issues have not yet been quantified by researchers.

Under the Sandia 6-category accident severity scheme, category 3 corresponds to an impact greater than the regulatory drop test, severe enough to damage the cask seals and to spall crud from the exterior of spent fuel. Category 3 is not associated with a fire. Category 4 corresponds to an impact sufficient to damage the cask seals and create cracks or splits in fuel cladding. Under category 4, gases and volatiles would enter the cask cavity. Wilmot notes that 10% of the rods were "arbitrarily assumed to fail during impact in those scenarios that are severe enough".[16] The percentages given for the SAI report were also chosen randomly by the NRC without any concrete basis. As stated, "This project was concerned with the identification of a phenomena, not the absolute magnitude of the source term; therefore, the choice of 10% initial failure, vs 20% or 1% was not an important consideration."[17] If the fuel cladding were sufficiently weakened by high burn-up embrittlement conditions or long-term storage conditions, category 3 accidents, involving release of CRUD on the exterior of fuel cladding could also release fuel particulates to the cask cavity and through the damaged seals, to the environment. That is, the lines between category 3 and category 4 accidents are not clear if cladding is embrittled or weakened. We assume therefore that in category 4 accidents, 100%, not 10%, of the fuel rods fail. While the industry is requesting a burnup credit, to account for the possibility that criticality is reduced, Commission staff might also consider

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[15] HK Manaktala, "Characteristics of Spent Nuclear Fuel and Cladding Relevant to High-Level Waste Source Term," Center for Nuclear Waste Regulatory Analyses, CNWRA 93-006, San Antonio, May 1993, p. 4-15.
[16] SAND80-2124, p. 39
[17] Rhyne, WR *et al*, *A Scoping Study of Spent Fuel Cask Transportation Accidents*, by Science Applications, Inc. for the Nuclear Regulatory Commission, NUREG/CR-0811, June 1979, pg. 5

a burnup **debit** because of the increased brittleness of cladding in high burnup fuel.

The probabilities calculated by Wilmot[18] for the six-category accident scheme[19] are 0.604, 0.395, 0.001, 1.E-6, 1.E-6 and 1.E-6 Because the lines between categories 3 and 4 are blurred and the arbitrary choice of 10% fuel rods damaged, we recommend that the probability of category 4 accidents be changed from 1.E-6 to 1.E-5. This change is incorporated into recommended inputs that follow. It is important that the Department of Energy and the Nuclear Regulatory Commission quantitatively assess the impact of dry cask storage and higher burnup on transportation safety.

Recommended RADTRAN IV Inputs

Analysis of 38 severe accidents shows that severe impact and fire conditions and probabilities have been underestimated by the Nuclear Regulatory Commission and Sandia. In particular, severe impacts due to falls from roadways and missing bridges have not been incorporated into these studies.

Further, analysis of fire duration and temperature in 38 severe accidents shows that the fire temperatures have greatly underestimated. Fires have burned for much longer than the regulatory limit of 1/2 hour and at far higher temperatures. In addition, three accidents involving explosives have created puncture environments far more serious than the regulatory limits.

To quantify this analysis and develop new probability estimates, a much larger data base of rail and highway accidents would have to be investigated.

Our analysis of 38 severe accidents has led to a change in fractional occurrences according to population density zones. The revised numbers are shown in Tables 9 and 10. These revised fractional occurrences according to population density zones lead to new inputs to RADTRAN IV which are

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[18] Wilmot, EL, *Transportation Accident Scenarios for Commercial Spent Fuel*, Sandia National Laboratories, SAND80-2124, February 1981.

[19] Luna, RE et al, "Response to the Report Entitled 'Transportation Risks: Appendix A, DOE Environmental Assessment - Analysis of RADTRAN II Model and Assumptions'," Sandia National Laboratories, SAND86-1312, June 1986.

calculated in Tables 13 and 14. For the 8-accident severity category scheme, we have employed the revised fractional occurrences according to population density zones. For the 6-accident severity scheme, we have employed the revised fractional occurrences according to population density zones and the revised fractional occurrences discussed earlier. The new inputs to RADTRAN IV are calculated in Tables 13a and 13b for trains, and Tables 14a and 14b for trucks.

Comparing Tables 5 and 13, we see that for the 8-category accident severity scheme, the inputs to RADTRAN IV are identical for categories I through IV. For categories V through VIII, the inputs are increased for suburban and urban population density zones. Since more people are located in urban and suburban zones, this will increase the risk calculated by RADTRAN IV under the 8. Similarly, for 6-category accident severity scheme, category 4 is increased by an order of magnitude. Further, the expected radiation releases in category 4 will also be increased by an order of magnitude for high burnup fuel. The inputs to RADTRAN IV for categories 5 and 6 in suburban and urban zones will also be increased. Since more people are located in urban and suburban zones, this will increase the risk calculated by RADTRAN IV under the 6-category accident severity scheme. Calculation of these risks is beyond the scope of this report.

Table 13a. Revised Accident Severity by Population Density Zone. Eight Severity Category Scheme - Train

NUREG-170 Accident Severity Fractional Occurrences

0.5	0.3	0.18	0.018	0.0018	0.00013	6E-05	1E-05	1

Multiply NUREG-170 accident severity fractional occurrences by overall accident rate,
  9.3E-7 railcar-accidents/railcar-km and fractional occurrences by population zone:

	I	II	III	IV	V	VI	VII	VIII
rural	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.29
suburban	0.1	0.1	0.4	0.4	0.4	0.4	0.45	0.48
urban	0.8	0.8	0.3	0.3	0.3	0.3	0.25	0.24

Train	I	II	III	IV	V	VI	VII	VIII	
rural	4.7E-08	2.8E-08	5E-08	5E-09	5E-10	3.627E-11	1.7E-11	2.697E-12	1.3E-07
suburban	4.7E-08	2.8E-08	6.7E-08	6.7E-09	6.7E-10	4.836E-11	2.5E-11	4.464E-12	1.5E-07
urban	3.7E-07	2.2E-07	5E-08	5E-09	5E-10	3.627E-11	1.4E-11	2.232E-12	6.5E-07

Divide each line by accident rate in each population density zone and normalize each row so that
  the sum of accident severity fractions in each population density zone is 1.

RADTRAN IV Inputs

Train	I	II	III	IV	V	VI	VII	VIII
rural	0.357	0.214	0.386	0.039	0.003857	2.79E-04	1.29E-04	2.07E-05
suburban	0.312	0.187	0.450	0.045	0.0045	3.25E-04	1.69E-04	3.00E-05
urban	0.571	0.343	0.077	0.008	0.000771	5.57E-05	2.14E-05	3.43E-06

Table 13b. Revised Accident Severity by Population Density Zone. Six Severity Category Scheme - Train

SAND80-2124 Accident Severity Fractional Occurrences

| | 0.604 | 0.395 | 0.001 | 1E-05 | 1E-06 | 1E-06 |

9.3E-07 railcar-accidents/railcar-km

Multiply SAND80-2124 accident severity fractional occurrences by overall accident rate, 9.3E-7 railcar-accidents/railcar-km and fractional occurrences by population zone:

	I	II	III	IV	V	VI
rural	0.1	0.1	0.3	0.3	0.3	0.29
suburban	0.1	0.1	0.4	0.4	0.4	0.48
urban	0.8	0.8	0.3	0.3	0.3	0.24

Train	I	II	III	IV	V	VI
rural	5.6E-08	3.7E-08	2.8E-10	2.8E-12	2.8E-13	2.7E-13
suburban	5.6E-08	3.7E-08	3.7E-10	3.7E-12	3.7E-13	4.5E-13
urban	4.5E-07	2.9E-07	2.8E-10	2.8E-12	2.8E-13	2.2E-13

Divide each line by accident rate in each population density zone (shown below).

Train	I	II	III	IV	V	VI	
rural	0.56172	0.36735	0.00279	2.8E-05	2.8E-06	2.697E-06	0.931893
suburban	0.029564	0.019334	0.000196	2E-06	2E-07	2.349E-07	0.049097
urban	0.029958	0.019592	1.9E-05	1.9E-07	1.9E-08	1.488E-08	0.049569

accident rates
rural	1E-07
suburban	1.9E-06
urban	1.5E-05

Normalize each row so that sum of accident severity fractions in each population density zone is 1.

RADTRAN IV Inputs

Train	I	II	III	IV	V	VI
rural	0.602773	0.394197	0.002994	3E-05	3E-06	2.894E-06
suburban	0.602164	0.393799	0.003988	4E-05	4E-06	4.785E-06
urban	0.604375	0.395245	0.000375	3.8E-06	3.8E-07	3.002E-07

Table 14a. Revised Accident Severity by Population Density Zone. Eight Severity Category Scheme - Truck

1

NUREG-170 Accident Severity Fractional Occurrences

0.55	0.36	0.07	0.016	0.0028	0.0011	8.5E-05	1.5E-05

Multiply NUREG-170 accident severity fractional occurrences by overall accident rate, 1.06 E-6 accidents/km and fractional occurrences by population zone:

	I	II	III	IV	V	VI	VII	VIII
rural	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.29
suburban	0.1	0.1	0.4	0.4	0.4	0.4	0.45	0.48
urban	0.8	0.8	0.3	0.3	0.3	0.3	0.25	0.24

Truck	I	II	III	IV	V	VI	VII	VIII
rural	5.83E-08	3.816E-08	2.226E-08	5.088E-09	8.904E-10	3.498E-10	2.703E-11	4.611E-12
suburban	5.83E-08	3.816E-08	2.968E-08	6.784E-09	1.187E-09	4.664E-10	4.055E-11	7.632E-12
urban	4.66E-07	3.053E-07	2.226E-08	5.088E-09	8.904E-10	3.498E-10	2.253E-11	3.816E-12

Divide each line by accident rate in each population zone (shown below).

rural	4.158E-01	2.722E-01	1.588E-01	3.629E-02	6.351E-03	2.495E-03	1.928E-04	3.289E-05	0.892153
suburban	2.175E-02	1.423E-02	1.107E-02	2.530E-03	4.428E-04	1.740E-04	1.512E-05	2.847E-06	0.050215
urban	2.917E-02	1.909E-02	1.392E-03	3.182E-04	5.568E-05	2.188E-05	1.409E-06	2.386E-07	0.05005

Normalize each row so that sum of accident severity fractions in each population density zone is 1.

RADTRAN IV Inputs

Truck	I	II	III	IV	V	VI	VII	VIII
rural	0.4661	0.3051	0.1780	0.0407	0.0071	0.0027966	0.0002161	3.686E-05
suburban	0.4331	0.2835	0.2205	0.0504	0.0088	0.0034644	0.0003012	5.669E-05
urban	0.5828	0.3815	0.0278	0.0064	0.0011	0.0004371	2.815E-05	4.768E-06

Rural acct rate	1.402E-07
Suburban acct rate	2.681E-06
Urban acct rate	1.599E-05

Table 14b. Revised Accident Severity by Population Density Zone. Six Severity Category Scheme - Truck

SAND80-2124 Accident Severity Fractional Occurrences

	0.604	0.395	0.001	1E-05	1E-06	1E-06

1.06E-06 accts/km

Multiply SAND80-2124 accident severity fractional occurrences by overall accident rate, 1.06E-6 accidents/km and fractional occurrences by population zone:

	I	II	III	IV	V	VI
rural	0.1	0.1	0.3	0.3	0.3	0.29
suburban	0.1	0.1	0.4	0.4	0.4	0.48
urban	0.8	0.8	0.3	0.3	0.3	0.24
Truck	I	II	III	IV	V	VI
rural	6.4E-08	4.187E-08	3.18E-10	3.18E-12	3.18E-13	3.074E-13
suburban	6.4E-08	4.187E-08	4.24E-10	4.24E-12	4.24E-13	5.088E-13
urban	5.12E-07	3.35E-07	3.18E-10	3.18E-12	3.18E-13	2.544E-13

Divide each line by accident rate in each population zone (shown below).

Truck	I	II	III	IV	V	VI	
rural	3.0780769	2.0129808	0.0152885	0.0001529	1.529E-05	1.478E-05	5.1065291
suburban	0.1576946	0.1031281	0.0010443	1.044E-05	1.044E-06	1.253E-06	0.2618797
urban	0.2188855	0.1431453	0.0001359	1.359E-06	1.359E-07	1.087E-07	0.3621683

accident rates
rural	2.08E-08
suburban	4.06E-07
urban	2.34E-06

Normalize each row so that sum of accident severity f4ractions in each population density zone is 1.

RADTRAN IV Inputs

Truck	I	II	III	IV	V	VI
rural	0.6028	0.3942	0.0030	2.994E-05	2.994E-06	2.894E-06
suburban	0.6022	0.3938	0.0040	3.988E-05	3.988E-06	4.785E-06
urban	0.6044	0.3952	0.0004	3.752E-06	3.752E-07	3.002E-07

Appendix A. Relationship Between Yielding and Unyielding Surfaces

To determine the probability of accident severity categories, the NRC and Sandia analyze a large data base of accidents. For rail and highway modes, accidents are categorized as head on and rear-end collisions with another vehicle, collisions into an object, and so on. For the parameter impact, for each type of accident, Sandia determines the relative velocity of the impacting vehicles, or the velocity into a real surface. The velocity into a real impacting surface is compared to the velocity into an unyielding surface. This section of the report analyzes the derivation of the relationship between these velocities.

The real "unyielding" surface for the Sandia tests is a 10 cm thick sheet of metal over 4.5 meter thick slab of reinforced concrete, the total mass of which was 690 tons. All this was backed with 1700 tons of earth. While the impacted surface is massive, the 80 ton cask plus railroad car is about 3% of this stopping body. Thus, the stopping body is expected to yield somewhat on impact.

The relationship between an unyielding surface and a yielding surface, needed for calculations of the probability of accident severity categories, is calculated using Hertzian contact theory. When a rigid sphere comes into contact with a plane, the compressive forces (P) begin to change the velocity of the sphere. The rate of change in velocity during impact can be described by the following equation:

$$m*(dv/dt)=-P \qquad \text{or} \qquad a=-P/m$$

At contact of the sphere with the plane, the displacement α of the elastic plane can be described by the following equation[1] After manipulation by multiplication and integration the resulting formula is

$$1/2(\alpha'^2 - v^2) = -2/5nn_1\alpha^{5/2}$$

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[1] SP Timoshenko, *Theory of Elasticity*. McGraw-Hill Book Company,1987, p. 412, eq.229.

where n = 1/m, and $n_1 = \left(\dfrac{4\sqrt{R}}{3\pi \dfrac{(1-v^2)}{\pi E}} \right)$, R = radius of the sphere, E = Young's modulus

of the half plane, v = Poisson's ratio and α is the displacement of the half plane, v is the velocity of the sphere at the beginning of contact and the velocity $\dot{\alpha}$ is the velocity of local compression. If $\dot{\alpha}$ = 0 the approach at the instant of maximum compression is found. It can be expressed as:

$$\alpha = \left(\frac{15\pi \dfrac{1-v^2}{\pi E} mv^2}{16\sqrt{R}} \right)^{2/5} \qquad \text{maximum displacement}$$

Note that the square on Poisson's ratio is missing from Eq. H-1 in Appendix H of NUREG-170. The square must be in the equation to correctly represent the pressure distribution on contact though it has a minor effect on the end results.

Moving one step further, the maximum value of the deceleration can be derived. To find this maximum deceleration, the half plane is presumed to have sinusoidal behavior. Sinusoidal waves by definition are waves of distortion, meaning all particles are moving perpendicular to the direction of the wave of propagation.. The deceleration is a maximum when the displacement of the half plane is at the extreme boundary. Assuming sinusoidal behavior, this maximum deceleration is:

$$A_{max} = \frac{0.1157\pi^2 v^2}{\alpha}$$

and the duration of contact, t is

$$t = \frac{2.94\alpha}{v}$$

In order to find the impact velocity ratio for various real elastic surfaces, we equate the decelerations for the "unyielding" steel target and the yielding surfaces. Solving this equation for v_y/v_s we get the following equation:

$$\frac{v_y}{v_s} = \left(\frac{(1 - v_y^2)E_s}{(1 - v_s^2)E_y} \right)^{\frac{1}{3}}$$

This equation is evaluated for different surfaces; water, soft soil, hard soil, soft rock and hard rock (answers similar to Table H-1 Appendix H NUREG-170).

The theory of Hertzian contact relies on certain assumptions which do not hold for severe accidents. First, impacts must be elastic, that is, objects must resume their initial form after the removal of forces. The approach and recessional velocities of impact are assumed to be identical and the restitution coefficient unity. For the full size Sandia tests, where casks impacted into the "unyielding" barrier at 27 and 62 mph, respectively, the casks were shortened by 1.6%, indicating a non-elastic collision. In addition, vibrations must be neglected, that is, the theory assumes that the time which the spheres remain in contact is very long in comparison with the period of the lowest mode of vibration. "There must be sufficient time for the passage of large numbers of elastic waves back and forth along the relevant directions of the two bodies."[2] This condition is expressed as

$$\left(\frac{V_o}{C_o} \right)^{1/5} \ll 1$$

where V_0 is the impacting velocity and C_0 is the velocity of longitudinal waves. For a thin rod, the velocity of longitudinal waves is

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[2] SC Hunter, "Energy Absorbed by Elastic Waves During Impact," *J Mech Phys Solids*, pp. 162 (1957).

$$C_o = \sqrt{\frac{E}{\rho}}$$

The ratios appear on the attached Table.

As seen, the ratios $\left(\dfrac{V_o}{C_o}\right)^{1/5}$ are not much less than one, as required for the theory to be valid, but range between 0.35 and 0.52 for a 60 mph impact. However, the energy lost in the transmission of elatic waves is not a significant fraction of the initial kinetic energy.

Generally, for an impact, the energy available to damage a container, E_D, is related to the incoming kinetic energy in the following way:

$$E_D = T_i - T_f - E_T$$

where T_i is the initial kinetic energy, T_f is the final kinetic energy and E_T is the energy absorbed by the surface[3]. E_T is composed of two parts, the energy due to the transmission of elastic waves, W, and the energy due to gross deformation of the surface, that is, the inelastic energy due to cratering the surface. Generally the final kinetic energy is less than 1% of the initial kinetic energy T_i.

If the ratio of the energy due to transmission of elastic waves W to the initial kinetic energy E is called λ, this may be expressed as

$$\lambda = C\left(\frac{\rho}{\rho_1}\right)^{1/5} \frac{(1+\nu)}{(gE)^{6/5}}\left(\frac{1-\nu}{1-2\nu}\right)\beta(\nu)\left(\frac{V_o}{C_o}\right)^{3/5}$$

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[3] Sandia Blue book

where $gE = 1 - v^2 + \left(\dfrac{1 - v^2}{\dfrac{E_1}{E}} \right)$

and $\beta(v)$ is a complicated function of v. For steel impacting on a steel surface, the energy disspitated due to elastic waves is 3.8% of the initial kinetic energy. Thus, for steel on steel, for a 60 mph impact, about 5% of the initial kinetic energy is lost due to the final kinetic energy and the energy due to elastic waves.

For the higher speed Sandia full scale tests, the cask impacted the wall at 62 mph[4]. The peak deceleration was 185g. One can calculate the maximum displacement and the time of contact from Hertzian contact theory. From Eq. xxx, we calculate the maximum displacement to be 0.48 m. From Eq. xxx, we calculate the time of contact to be 0.051 seconds, which was the experimental result.

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[4] M Huerta, Sandia

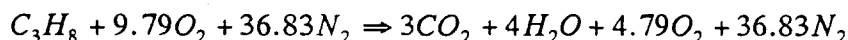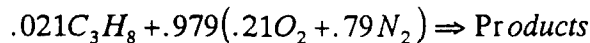# Appendix B. Calculations of Flame Temperatures

In order to find the range of flame temperatures, a simple and basic procedure was used. This range represents the lower to upper flammibility limit of each burned material. The flammibility limits are "the composition limits within which a flame can propagate and are expressed as concentrations of the fuel in a specific oxidant /dilutant mixture at a specific temperature and pressure. "As can be seen by the table this range of flame temperatures are given for the corresponding flammibility limits. The two lists of flame temperatures correspond to heat capacities at 727°C and at 25°C (room temperature) respectively. The procedure in solving these flame temperatures is best explained by giving an example of a common chemical (i.e. acetone).

Material Burned: **Propane**   Heat Capacities at 25°C

Molecular Structure: C_3H_8 Lower Flammability Limit=2.1%

$$.021 C_3H_8 + .979(.21 O_2 + .79 N_2) \Rightarrow \text{Products}$$

$$C_3H_8 + 9.79 O_2 + 36.83 N_2 \Rightarrow 3CO_2 + 4H_2O + 4.79 O_2 + 36.83 N_2$$

Heat capacities of the products:

$$CO_2 : 3 \times 37.1 = 111.3$$

$$H_2O : 4 \times 33.6 = 134.4$$

$$O_2 : 4.79 \times 29.4 = 140.8$$

$$N_2 : 36.83 \times 29.1 = 1071.75$$

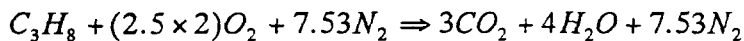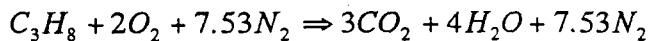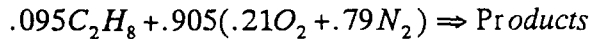$$\overline{c_p} = \text{Total Heat Capacity} = 1458.3 \text{ J/K}$$

$\Delta H_c = 2044$ kJ/mol

Flame Temperature Equation: $T^F = 298 + \dfrac{n \times \Delta H_c}{\overline{c_p}}$ $n = \#$ of moles

$$T^F = 298K + \frac{(1mol)(2044000J / mol)}{1458.3J / K} = 1699.6K$$

$$T^F = 1699.6 - 273.15 = 1427°C$$

Upper Flammibility Limit=9.5%

$$.095C_2H_8 + .905(.21O_2 + .79N_2) \Rightarrow Products$$

$$C_3H_8 + 2O_2 + 7.53N_2 \Rightarrow 3CO_2 + 4H_2O + 7.53N_2$$

$$C_3H_8 + (2.5 \times 2)O_2 + 7.53N_2 \Rightarrow 3CO_2 + 4H_2O + 7.53N_2$$

Heat Capacities of the products:

$$CO_2: 3 \times 37.1 = 111.3$$
$$H_2O: 4 \times 33.6 = 134.4$$
$$N_2: 7.53 \times 29.1 = 219.1$$

$$\overline{c_p} = \text{Total Heat Capacity} = 464.8 \text{ J/K}$$

$\Delta H_c = 2044$ kJ/mol

$$T^F = 298K + \frac{(1mol)(2044000J / mol)}{464.8J / K} = 4695.6K$$

$$T^F = 4695.6 - 273.15 \approx 4422°C$$

These calculations for both lower and upper flammability limit are contingent on some assumptions. Primarily it is assumed that there is as much oxygen as needed in the air. This is important at the upper flammability limit since the amount of oxygen to balance the chemical reaction is deficient in reactants. It was then presumed that an unlimited supply of oxygen was available. The more oxygen available will make the flame temperature much higher. Therefore the range given in the table spans from when there is just enough oxygen to cause a fire to when there is an unlimited supply.[5]

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[5]Note: All calculation procedures were taken from; The SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy ,MA, 1988.